A Passively Operated Spool Valve for Drain-Down Freeze Protection of Thermosyphon Water Heaters

MASTER

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1. INTRODUCTION

This report describes the work done by Sunspool Corporation to extend the existing Sunspool drain-down valve technology to provide passive drain-down freeze protection for thermosyphon-based solar water heaters. Sunspool Corporation manufactures an electrically driven valve used to drain the solar collectors of open loop active systems. Three passive actuators to drive the basic Sunspool valving mechanism were designed, fabricated and tested. In parallel with the development work, an article on the drain-down thermosyphon systems was published in Solar Engineering magazine. The response generated from the article and initial field testing has provided information regarding the potential marketability of the drain-down freeze protection for thermosyphon systems.

2. PROBLEM DEFINITION AND REVIEW OF EXISTING THERMOSYPHON SYSTEMS

In the continental United States, virtually all solar collectors will be exposed to freezing conditions on a yearly basis. Even in the temperate climate of Southern California and Florida, solar systems must be protected during a several week period in the winter when freezing temperatures occur. Solar system designers for active systems have been struggling to provide adequate freeze protection for years and have yet to completely solve the problem.

There are three generic methods of freeze protection used in the majority of U.S. solar/DHW systems: 1) Heat Exchange Systems use antifreeze which is circulated through the solar collectors. The antifreeze is isolated from the drinking water by a heat exchanger in the solar storage tank. 2) Pump-on Recirculation Systems pump hot water from the storage tank through the collectors to keep them warm when freezing is imminent. 3) Drain-down and Drain-back Systems drain the water out of the solar collector piping to avoid freeze damage. Drain-down systems drain the collector array of the pressurized, potable water when freezing conditions are detected. Drain-back systems require a low pressure reservoir containing a fixed quantity of treated water which is pumped up through the collector array during normal operation. A heat exchanger transfers the energy from the treated water loop to the potable water during solar energy collection. When the pump is stopped, the treated water drains from the collectors back to the reservoir, thus protecting the collectors from freeze damage. A detailed description of these systems appears in Appendix A.

Unfortunately, most of these freeze protection methods cannot practically be applied to thermosyphon systems. Heat exchanger systems add substantially to the cost and complexity of the system and degrade thermal performance significantly due to the lack of forced circulation on either side of the heat exchanger surface. Antifreeze solutions often introduce increased fluid viscosity -- a factor which can affect the delicate flows nurtured by the thermosyphon potential. A pump-on recirculation concept is not feasible because thermosyphon systems do not have circulation pumps. Drain-back methods suffer most of the hardware disadvantages of heat exchange systems, are further complicated by the geometric constraints of thermosyphon systems and require the use of some form of pumping device.

To date, the primary freeze protection method employed for thermosyphon systems has been the use of electrical resistance heaters placed behind the solar collector absorber plate. A thermostat detects the approaching freezing condition and the heater is turned on, thereby heating the absorber plate, until it reaches a safe temperature. The thermostat cycles the heater on and off during the freezing condition as needed. There are two serious drawbacks to this approach: a) The technique uses a valuable high quality energy source for freeze protection; and b) It is totally ineffective during power failure, a condition often associated with cold weather conditions. Also, this type of freeze protection would be totally ineffective in Florida and other parts of the country where utilities have scheduled "brown-outs" to conserve energy by shutting down power sequentially to different areas in the power grid.

Some other freeze protection techniques for thermosyphon systems have surfaced in the last six months. The first is a thermally actuated bleed valve connected to the collector piping (Figure 1). As the temperature falls close to a freezing condition, the bleed valve opens slightly to permit a restricted flow of water from the thermal storage tank through the solar collectors -- thereby heating the collector. The water is discharged near the collector as shown in Figure 1. Unfortunately, the technique uses the thermal energy collected by the solar system during the previous day. In addition, as the water is discharged to the outside environment, the functioning of the device may be adversely affected in hard freeze areas where the device is exposed to severe outside weather conditions. These products are somewhat new and the lifetime is in question. This approach is probably not feasible in areas other than the moderate climates of the Sun Belt.

A second approach uses a non-freezing refrigerant in the collector piping. The fluid is similar to the refrigerant used in a common household refrigerator. The collector loop is isolated from the drinking water by a heat exchanger. The refrigerant transfers the energy from the collector to the storage tank by vaporizing at the collector under sunny conditions and then discharging the latent heat of evaporation as it condenses at the heat exchanger surface. This type of system is relatively expensive and the heat exchanger reduces the overall efficiency of the system.

The Sunspool valve-based design for providing freeze protection for thermosyphon systems is an extension of the drain-down concept used in active systems. In general, when freezing conditions approach, the valve

Figure 1 Thermosyphon Solar Water Heater with Bleed Valve

isolates the high pressure water in the storage tank from the solar collectors. The valving then permits the collector water to drain the exposed collector and piping, thus protecting them from freeze damage. The valve will fill the collectors and permit thermosyphon flow to be established when the collectors are safe from freezing temperatures and solar energy is available. The following section of this report describes the operation of the existing Sunspool valve. The reader should be familiar with the valve's characteristics to best understand the passive actuators presented in the later sections.

3. A DETAILED MECHANICAL DESCRIPTION OF THE SUNSPOOL VALVE

The current production version of the Sunspool drain-down valve appears in cross-section in Figure 2. The basic design is that of a spool valve, employing a cylindrical spool (Part 3) which moves axially in a mating cartridge (Part 2) to open and close o-rings at the two operating extremes (drain and operate) to perform the valving function. Figure 2 shows the valve in the operate position, permitting unrestricted flow between ports 1 and 2. In an active system, the flow path connects the pump/tank to the collector supply line. The returning flow from the collector array enters port 3 and proceeds through a floatable check ball and out port 4. Port 4 is connected to the thermal storage tank.

The drain command moves the spool shown in Figure 2 approximately 1/2" to the left. In this position, the pressurized supply line from the pump/tank is isolated and sealed. Ports 2 and 3 are exposed to the atmospheric drain port represented by the barbed hose fitting (Part 9).

The actuation of the spool is accomplished by two phase-change heat motors (Part 22). These devices are mounted back-to-back in order to obtain the necessary spool travel. Manufactured by Robertshaw, the heat motors feature a constrained wax charge which expands at a preselected temperature (in the present design, approximately 165°F). The heating is provided by a small power resistor (Part 23) which communicates with the heat motors through an aluminum support member (Part 24). Power is supplied to the resistor until the structural member (Part 18) moves to open the microswitch (Part 33). This action breaks the circuit to the

Figure 2. Sunspool Valve Cross-section

power resistor. The heat motors then cool and retract slightly, moving the spool back to the left and in the direction of the drain position. The return force is provided by a 30 lb. spring (Part 17).

As long as power is supplied to the valve, the valve actuator "hunts" around the microswitch and maintains the spool in the "operate" position. A small oscillation occurs at the "operate" point, with a characteristic 0.040" envelope and a 2-minute period. During this time the microswitch cycles, turning the power on and off on an identical period. When power is interrupted to the entire assembly, the main return spring drives the spool fully to the left and draining occurs.

The power resistor is sized to provide a maximum of 7 watts at operating voltage intended for the particular valve (e.g., 12, 24 or 115 VAC models). However, the average power consumption is held to 2 watts.

4. OVERVIEW OF THE DRAIN-DOWN FREEZE PROTECTION PIPING CONFIGURATIONS

This section describes two piping configurations used to integrate the Sunspool valve with the thermosyphon system. A detailed description of the passive actuators developed appears in the following section.

A. Combined Valve Configuration

Figure 3 depicts the piping configuration outlined in the original proposal. The Sunspool valve is placed between the tank and the solar collector. When actuated to the operating position, the valve would first fill the array and then permit thermosyphon flow. The valve itself is located in close thermal contact with the storage tank and is insulated to prevent freezing of the valve body. The port normally used for draining in the active version of the Sunspool valve is used instead to admit air to the collector array during the drain operation. The actual draining of the array would be undertaken by a thermostatically operated single-port valve. This valve will remain closed above, say, 55°F, and open below that temperature. Thermostatically operated valves manufactured by Eaton Corporation, Freezeton and H&H Products were tested. They all operated well in conjunction with the test system. It is unclear if these devices can withstand the extreme temperatures variations experienced by solar systems.

A spring biased check valve was designed as a replacement to the thermostatically operated single-port valve. The check ball is

Figure 3 Combined Valve Configuration

spring loaded to open when the pressure in the collector piping is reduced upon opening of the Sunspool valve. The ball opens an orifice to drain the collectors. When refilling occurs, the pressurizing water forces the ball to close against the bias spring and close the orifice.

In summary, the Sunspool valve will isolate city line pressure from the array when freezing conditions approach. The normal drain port will act as an air vent. A separate, single-port valve will drain the array of the resident water.

B. Direct Drain-down Configuration

The Sunspool valve can also provide for draining of the collector array with a modification to the piping as described above. As seen in Figure 4, the Sunspool valve has been divided, both figuratively and literally, into two major subcomponents. By cutting the standard valve at the appropriate point, the check valve assembly has been isolated and placed in the position shown in the schematic. The remaining portion of the valve (functionally, a 3-port valve) has been placed below the lower manifold of the collector array. The spool, cartridge, and drive assembly in the 3-port valve is a stock Sunspool drive assembly.

The important advantages of this approach are as follows:

- 1) Due to the separation of the checking and valving functions, the

Figure 4 Direct Drain-down Configuration

thermosyphon piping arrangement can be much more flexible.

- 2) The point of drainage is moved from an outdoor location to an indoor (or otherwise protected) location.
- 3) The need for a thermostatically operated single-port valve at the bottom of the array is eliminated. This removes a component, which may be prove to be one of the weakest links in the system. The bleed valve must withstand temperatures ranging from collector stagnation (300°F) down to subfreezing. The lifetime of the bleed valve's thermally actuated drive mechanism under these environmental conditions is questionable.

Note, however, that this revised configuration may not be readily adaptable to "packaged" thermosyphon systems such as those manufactured by Solahart. The cold water supply line to the bottom of the collector must be diverted to a point below the collector. Logically, this point could be within the attic plenum on roof-mounted systems.

5. DETAILED DESCRIPTION OF PASSIVE VALVE ACTUATORS

A. Photovoltaic Design

This approach uses a direct conversion photovoltaic (PV) array to provide power to the existing electrically driven Sunspool valve (Figure 5). The PV array provides electrical power to the Sunspool valve when solar radiation is available. The heat motor actuator, powered by a small resistive heater, moves the spool to the operate position. A small PV array of approximately 1 square ft automatically controls the Sunspool valve; the thermosyphon system is filled only when solar energy is available and drains each day when the sun sets. The freeze protection circuitry/valve operation is governed by two elements: the PV array and a bimetallic snap-action thermostat. Figures 6 and 7 show the PV array and the Sunspool valve, respectively, installed on the test stand.

Several manufacturers were contacted to find a PV array that would provide the appropriate power and voltage levels for the Sunspool valve. The most helpful manufacturer was Motorola's Semiconductor Group in Phoenix, Arizona. They have done extensive research in the use of photovoltaic arrays to drive small DC powered circulation pumps for active solar/DHW systems. After testing the Sunspool valve in their lab, they recommended their model MSP13A10 with a nominal power output of 10 watts. The array, rated at 12 volts and made with 33 small silicon solar cells, is shown in Figure 6. The operating curve shown in Figure 8 shows the resistive load of the Sunspool

Figure 5 Photovoltaic-based Actuator Concept

Figure 6 Motorola Photovoltaic Array

Figure 7 Sunspool Valve used with Photovoltaic Design

electric actuator matched against the PV array output. The intersection of the curves is the operating point for the PV/Sunspool circuit. The load curve falls close to the maximum power available from the array.

Figure 9 shows the operating characteristics for the PV array/Sunspool valve combination. The available insolation for a typical day is plotted as a function of time of day. The solid line depicts the period that the valve was actuated to the operating position and thermosyphon flow was established. In the early morning, the PV array does not provide enough electrical energy to actuate the valve. However, once the insolation reaches 120 Btu/hr-sq. ft, the valve moves to the operate position and remains there until the insolation levels drop below 120 Btu/hr-sq. ft at the end of the day. Under this configuration, the thermosyphon system is filled and operating when 95 percent of the day's solar energy is available. A nominal 5 percent is lost in the early morning and late afternoon.

Further investigation was required to determine if the varying PV DC voltages would harm the limit switch used in the Sunspool valve (refer to Appendix A for a description of the switch operation), which is rated for 3.0 million cycles under AC voltage conditions. The manufacturer of the switch, Honeywell/Micro Switch, would not provide a lifetime rating for use in DC circuits. Honeywell engineers indicated that arcing across the switch contacts present under DC conditions might significantly reduce the lifetime of the

Figure 8 Operating Point for Combined Photovoltaic and Sunspool Valve Operation.

Figure 9 Operating Characteristics of Photovoltaic System

device. The PV/Sunspool configuration cycles the switch every 2.0 minutes for eight hours each day. This translates to approximately 180,000 cycles each year.

A test rig was set up to cycle the switch under DC conditions to determine switch life. The switch operated properly through 7.0 million cycles at 12 VDC during the two week accelerated test period, for an equivalent 70 years of operation. The samples were then sent to Honeywell for their inspection and recommendations. Honeywell disassembled the switch and noted slight pitting at the contact surfaces, but approved the switch use for DC conditions. We have concluded that the switch should function well in the PV application.

Overall, the photovoltaic-based system operational performance meets the requirements for drain-down freeze protection. The control characteristics fit elegantly with the overall system. This passive control feature has prompted some of Sunspool Corp.'s OEM customers to develop and market PV-based systems to drive both the pump and the Sunspool valve as in typical active solar system installations. solar system installations. This approach has converted what were once active systems into totally passive systems. The obvious drawback to the PV design is the cost of the silicon cells. However, we are encouraged that our customers have found a niche in the market for their use. A comparison of the relative costs of the alternate actuators is deferred to the next section.

B. Refrigerant-based Bellows Design

Refrigerant-based valve actuators are used in many temperature dependent valving applications in the HVAC industry. Typically, the sensing bulb is placed in the temperature environment to be measured and bellows is positioned to actuate the valve mechanism. In our application, the sensing bulb is placed in the solar collector, and the bellows replaces the heat-motor actuator in the Sunspool valve. As the temperature of the collector rises above approximately 75°F, the bellows expands to move the spool to the operate position. When the temperature drops below 50°F, the bellows contracts and the spool moves to the drain position.

Figure 10 shows the prototype bellows assembly manufactured to our specifications by Robertshaw Controls Co. The bulb is placed in the collector (Figure 11) so that energy collection can occur during sunny days, even if the outside air is below 50°F. Care must be taken to minimize outside pipe runs to reduce the exposure of the piping to freezing temperatures during the day. The 6 ft capillary tube connects the sensing bulb with the bellows assembly positioned inside the Sunspool valve (Figure 12).

Figure 13 shows the vapor pressure-temperature properties of butane (Refrigerant 600), the refrigerant used in the prototype. State point 1 indicates the properties of the refrigerant at 50°F; the vapor pressure is 8.0 psig, which acts on a 2 square inch piston. The 16 lbf force exerted by the bellows is not enough to overcome the

Figure 10 Prototype Bellows Assembly

Figure 11 Sensing Bulb Location

Figure 12 Bellows Mechanism in Sunspool Valve

VAPOR PRESSURE-TEMPERATURE CURVES

ROBERTSHAW CONTROLS COMPANY • 155 HILL STREET • MILFORD, CONN. 06460

Figure 13 Vapor Pressure-temperature Curve for Refrigerant 600 (Butane)

20 lbf force of the return spring and so the valve remains in the drain position. As the temperature increases at the collector and sensing bulb, the vapor pressure increases until it reaches 24.0 psig at state point 2. The resulting force pushing on the spool is 48 lbf. This is sufficient to overcome the return spring and push the spool to the operate position. Importantly, the refrigerant selected can withstand temperatures up to 300°F, which is high enough to cope with the high stagnation temperatures associated with high performance solar collectors.

Figure 14 shows the fill and drain characteristics of the bellows/valve assembly, as depicted on a spool travel vs. sensing bulb temperature curve. The curve plots the spool travel in the valve as a function of the temperature at the sensing bulb. Note the hysteresis present in the device: the curve falls differently during temperature rise as compared to temperature fall. This hysteresis does not adversely affect our application, since we are interested only in the extreme points of the curve. The device should always be in the drain position (or .000" travel of spool travel) when the temperature drops below 50°F and the spool should be in the operate position (or .350" spool travel) when the temperature is above 75°F. The shaded areas in Figure 14 depict these two regimes.

The temperature characteristics of the bellows assembly are very impressive. The valve moves to the drain and operate position positively on temperature signal. The capillary tube is delicate, however, and requires much care in installation. In 1000 piece

Figure 14 Plot of Spool Travel vs. Sensing Bulb Temperature

quantities the price is quoted at approximately \$100 each. At this price, we find the PV-based system and the bellows concept compare favorably when all characteristics are considered.

C. Heat Motor Cable-drive Design

During the development phase of the project, a new actuation concept based on the heat motor was conceived. This approach uses a push-pull control cable similar to a bike brake cable, which is affixed to the Sunspool valve spool at one end and the heat motor on the other. The heat motor is positioned in the collector enclosure and charged with a wax which changes phase at approximately 65°F. The approach is attractive because of the relatively low cost of heat motors.

Figure 15 shows the heat motor assembly drawing. As the temperature rises to safe levels above 70°F, the heat motor will expand and push the cable until the spool bottoms out in the operate position. When the heat motor is exposed to cooler temperatures, the heat motor will retract and the spool will be returned to the drain position by the return spring. Figure 15 shows the device in the operate and drain position.

The first prototype assembled for testing is shown in Figures 16, 17 and 18. This prototype failed to provide adequate travel to the spool to ensure proper operation. The spool travel vs. heat motor temperature characteristics show the problems of the first prototype

Figure 15 Heat Motor Drive Assembly Drawing

Figure 16 Heat Motor Cable Drive Assembly

Figure 17 Heat Motor Assembly Mounted to Solar Collector

Figure 18 Sunspool Valve Used for Heat Motor Actuator

Figure 19 Plot of Spool Travel vs. Heat Motor Temperature for Small Heat Motor Actuator

(Figure 19). Even when heated to 140°F , which is much too high for this application, the assembly had just barely enough travel (0.280") to fill the collector array. For effective thermosyphon operation, the spool must travel at least 0.350". A larger heat motor with a longer stroke was required to provide the full spool travel needed.

Figure 20 shows the larger power pill which was added to the existing cable/valve assembly. The device worked very well with the larger heat motor and the temperature vs. stroke characteristics are shown in Figure 21. The Robertshaw Controls Co. design engineers are confident that a heat motor based on the smaller, cheaper size can be fabricated to provide the required travel. Unfortunately, there was not enough time to fabricate the part for inclusion in the final report. However, the prototypes for smaller heat motors are on order and will be tested once received.

Figure 20 Small and Large Heat Motors used for Prototypes

Figure 21 Spool Travel vs. Heat Motor Temperature for Large Heat Motor Actuator

6. COST COMPARISON OF ALTERNATE ACTUATORS

Table 1 shows the component costs estimated for quantities of approximately 1000 pieces. The photovoltaic approach is significantly more expensive at the present time. However, current PV array costs are at the \$20/watt level, and we expect, as do the PV manufacturers, to see a reduction to approximately \$10/watt by 1985. The cost for the bellows design ended up to be higher than originally estimated by Robertshaw. They are working on a cheaper design. The heat motor design shows promise, being much less expensive than the other actuators.

7. OPERATING CHARACTERISTICS FOR SUNSPOOL-BASED THERMOSYPHON SYSTEM

A. Thermosyphon Test Stand

The test stand is a fully operational and instrumented thermosyphon system located at the Sunspool facility. The system features a steel frame which positions the 60 gallon insulated, pressurized storage tank horizontally above two high performance solar collectors tilted at 45° . The assembly has been designed to be moved, intact, with the use of a forklift.

Figure 22 is a photograph of the system. The covered trench in the foreground of the picture houses the pressurized water supply piping, 115 VAC power, and thermocouple and instrument wires to connect the system to the data collection station inside the building. Figure 23 shows different system components in an isometric drawing.

Table 1 Cost Comparison of Alternate Actuator Concepts

COMPONENT	PV DESIGN C. 1982	PV DESIGN C. 1985	BELLOWS DESIGN	HEAT MOTOR DESIGN
SUNSPool VALVING MECHANISM	30.00	30.00	30.00	30.00
ELECTRIC HEAT MOTOR ACTUATOR	2.50	-	-	-
BELLOWS ACTUATOR	-	-	100.00	-
HEAT MOTOR/CABLE DRIVE	-	-	-	10.00
PV ARRAY	200.00	100.00	-	-
TOTAL	232.50	130.00	130.00	40.00

Figure 22 Thermosyphon Test Stand

Figure 23 Isometric Drawing of Thermosyphon Test Stand

The system is piped in the direct drain-down configuration. When the Sunspool valve is in the operate position and thermosyphon flow is established, the water from the bottom of the tank moves down the downcomer (1) and Sunspool valve (2) to the lower collector manifold (3). The arrows on the drawing indicate the water flow path during thermosyphon conditions. The water rises through the solar collectors and check valve (4) into the top of the storage tank (5). In the drain position, the Sunspool valve closes the line from the bottom of the tank and drains the collector piping through the drain port (6). The check valve automatically closes the piping from the top of the tank. The vacuum breaker (7), positioned below the check valve, permits the flow of air into the piping to allow draining of the solar collector.

The test stand is fitted with a water meter to determine water usage and a timed solenoid valve (8) to simulate a hot water load on the system. The solenoid valve is connected to a timer which automatically discharges 30 gallons of hot water from the top of the tank at 7:30 am and again at 7:30 pm each day. The replacement cold water flow registers on the water meter and is piped to the bottom of the tank.

B. Instrumentation

Additional equipment is used to monitor the system performance and operating characteristics. Thermocouples are placed in strategic locations on the piping, and a pyranometer measures the insolation

levels (Figures 23 and 24). A pressure switch installed near the collector piping indicates when the system has been drained (item 9, Figure 23). A low voltage circuit is wired through the pressure switch and reads +3V when the collectors are drained and 0V when the collectors are pressurized with water. Connections to the instruments are made through an underground conduit connecting the test stand with the data collection equipment inside the building.

A Monitor Labs datalogger and Techtran tape recorder/reader are used to collect the data (Figure 25). The datalogger can read up to 10 channels at 5-minute intervals and record the information, via the Techtran unit, on cassette tape. The data can then be read into the IBM Series/1 computer for reduction and printout (Figure 26). (Note: The Monitor Labs datalogger is the only equipment shown purchased under the contract. All other equipment was in place at Sunspool before the contract began.)

C. System Performance

The test rig provides an effective test stand to investigate the passive actuators and performs well as a thermosyphon system. Within minutes of the initial filling, the system started thermosyphon flow. By the end of the first day of operation, the tank temperature reached 150°F. The system operated without freeze damage from any of the test setups throughout the winter of 1981-1982.

The system has been operating for the last 12 months, delivering 60

Figure 24 Pyranometer and Thermocouple

Figure 25 Data Collection Station

Figure 26 Tape Reader and IBM Series I Computer

gallons of hot water every day. Each morning the system starts out at ground water temperature, approximately 55°F. By the end of the day, under clear sunny conditions, the top of the tank consistently exceeded 120°F during the winter and 150°F during the summer. These observations and the data presented in Figure 27 verify that the test rig correctly simulated the operation of typical thermosyphon systems. Figure 27 shows a plot of the system temperatures, the available solar insolation, and system status (i.e., filled or drained) during the day.

These data should give the reader a good idea of the typical operating characteristics of the system. In the early morning until approximately 8:30 am, the collector inlet and outlet temperatures follow the ambient air temperature closely. These data were collected with the photovoltaic powered Sunspool valve, so the system is drained during this time. Between 8:30 and 10:00 am the collector temperatures slowly rise, reflecting a modest energy gain from the low insolation levels. When the insolation reaches approximately 120 Btu/hr-sq. ft, the PV array powers the Sunspool valve, fills the system, and thermosyphon flow begins. The collector inlet temperature dips as the cold water from the bottom of the tank is pushed into the collector. As the day progresses, the collector temperatures rise, reflecting the addition of energy to the system. By the end of the day, the tank has reached approximately 135°F. As the insolation drops below 100 Btu/hr-sq. ft, the valve moves to the drain position, thermosyphon flow is stopped, and the collector temperatures fall to ambient air temperatures during the night.

Figure 27 Typical Operating Temperatures and Insolation Levels for the Thermosyphon System

Appendix C contains computer printout of the data for typical day of operation.

The system operates with a flowrate of approximately 0.2 gpm. This relatively low flowrate, approximately 1/5 the flowrate for active solar/DHW systems, concerned us initially. Several tests were performed to verify that the Sunspool valving mechanism and check valve did not impose a pressure drop that might reduce the thermosyphon flow.

A flow visualization device was assembled to aid in the pressure drop analysis. The apparatus is designed to inject dye into the high pressure water in the system piping. The dye is then viewed in a transparent section of piping to indicate flow (Figure 28). Isolated by a metering valve, the ink reservoir is connected to the system piping by a pressure probe inserted into a "Pete's Plug" fitting. Because the dye is pressurized to a higher pressure than the system piping, the dye will flow into the water as the metering valve is opened.

During the flowrate experiments, there was no perceptible change in the flow rate characteristics of the system when the ball was removed from the check valve. The system was also operated with the spool valving element removed from the Sunspool cartridge. Again, there was no measurable change in the flowrate. We have concluded that the use of 3/4" pipe and the piping geometry are probably responsible for the low flowrates in the system.

Figure 28 Flow Visualization Apparatus

In summary, the test system was effective in simulating the operation of typical thermosyphon systems. Because our main concern was the operation of the actuators, the low system flowrates did not affect our testing. However, future work with the test stand would benefit from repiping the system to reduce the overall pressure drop.

7. FIELD TESTING

A. Purpose and Description of Program

In addition to the in-house testing of Sunspool-based thermosyphon systems, a limited number of "unassisted" field tests were carried out. These tests served as a means of evaluating marketing and technical factors that were considered important for future commercialization of the product as well as a method of evaluating design criteria with respect to eventual use of the product in the field. Test systems were located throughout the United States and included installations in New York, California, Texas and Florida. Because of the very limited availability of the more advanced Sunspool actuator mechanisms (i.e., refrigerant-operated and heat motor cable drive versions), field testing was limited to Sunspool models with conventional actuators. The two approaches to drain-down freeze protection of thermosyphon systems in this category are the inverted Sunspool used in combination with a thermostatic drain -- the multi-component approach -- and the modified 3-port Sunspool with a separate check valve -- the direct drain-down approach.

The primary emphasis of the field testing program was to gather working information from as wide a variety of system types and geographical locations as was possible in a limited sample. Field tests were done in harsh, moderate and fair weather areas with a fairly wide variety of system components. In this way, we were able

to make a reasonable working evaluation of the compatibility of the drain-down approach to freeze protection under a variety of weather patterns, while at the same time gathering information concerning installation problems, component performance and compatibility of the system design with existing architecture. Since most of these tests were arranged through product distributors or commercial contractors, the results are primarily qualitative. The field test installations were solicited through advertisements in solar publications and by direct contact with interested parties through the Customer Service Department at Sunspool Corp. Although suggested approaches based on our in-house testing were provided, the actual installation details and system design were left to the discretion of the parties involved with the installation.

By minimizing supervision of these test systems, we sought to discover any common installation or design problems that might be encountered by the installing contractor, homeowner. We were pleased to find that there were few problems related to the design of the Sunspool valve; rather, most problems that were encountered were due to structural constraints or to simple installation errors, and even these problems were minimal.

B. General System Details and Field Test Examples

Control strategies for the test systems were generally very simple. The most common approaches are as follows: use of a low voltage (12 or 24 VAC) circuit with temperature activated snap switches; use of a

small photovoltaic array; or use of a photovoltaic array in combination with temperature activated snap switches. The first method uses an external power source to activate the Sunspool valve: when the temperature falls below the snap switch set point (usually 45-50°F), the circuit is broken and the valve is de-energized. The photovoltaic approach simply provides power to the valve when insolation is sufficient to raise the voltage output above the operating threshold of the valve. The last method combines the advantages of the first two while protecting against the theoretical possibility of having sufficient light for the PV array to energize the Sunspool and fill the system but insufficient heat to bring the collector array above freezing temperatures. One other control strategy that was suggested by one of the test subjects was the use of a photoelectric switch (similar to those used to control outdoor lights) in a 115 VAC circuit to provide system control behavior similar to that of a simple photovoltaic panel, but this alternative was never implemented.

The more conventional test systems generally employed a storage tank located in an attic or attic space with collectors mounted on a nearby roof area or ground structure. Our oldest test system is located in Los Altos Hills (Northern California) and has been in operation for approximately 18 months. This system consists of two 4 x 8 double-glazed copper flat plate collectors and a 120 gallon auxiliary hot water storage tank in combination with a 60 gallon gas water heater. Employing the multi-component drain-down approach, the

system provides a significant portion of both the domestic hot water and space heating requirements of a two-person household. The storage tank is located in the attic and the collectors are mounted on a nearby roof area with unobstructed solar access. The control strategy is a low voltage circuit with snap switches.

A similar system in Tacoma, Washington has been in operation for just over a year. Installed by the Small Tribes Organization of Western Washington as the final system in a series of 10 thermosyphon systems, the Tacoma installation is part of the Appropriate Technology Grants program for installation of solar assisted domestic hot water systems on the homes of low income Native Americans. The system provides domestic hot water for a family of four and consists of two single glazed copper flat plate collectors, a 60 gallon auxiliary hot water storage tank and a 40 gallon electric hot water heater. The control strategy is a low voltage snap switch circuit as above, but employs the direct drain-down approach. The solar tank is located in the attic, above the collectors, which are mounted on a ground structure on the south side of the house. One unusual and undesirable variation in this system is that the cold water line runs above ground from the house to the Sunspool valve (located outside) and the collectors. Although both the cold water supply line and the Sunspool valve are heavily insulated, this is a non-optional placement of both and hence the system may be subject to freezing during periods of prolonged cold weather. The system has, however, weathered one winter season already with no problems, and neither the homeowner nor the installing organization consider our concerns

justified given the faithful performance of the system to date.

C. Difficulties and Potential Problems

Perhaps the most common difficulty mentioned by those involved with the installation of drain-down thermosyphon systems is that of fitting the installation to an existing structure. Because it is necessary to locate the tank above the collectors, structural limitations sometimes preclude convenient retrofit installations. Older structures are often not strong enough to handle the weight of an upstairs storage tank, and many homes simply do not have sufficient space for such an installation.

In addition to the problems of fitting the system to the existing structure, a number of other potential problems have been mentioned. The majority of these problems are universal complaints in the solar industry: those related to inexperience or lack of sufficient expertise of the installer. Since the solar industry is still in its infancy, both in technology and organization, many of the people who are responsible for the installation of solar systems have little or no technical background. Improper installation can result in poor system performance or even damage to the system that is beyond the control of the manufacturer. This is a strong argument in favor of simplicity of design, and the simple overall concept of the Sunspool-based thermosyphon system in conjunction with the self-controlling feature of the photovoltaic control strategy make it a highly desirable alternative.

Surprisingly few specific problems have been reported in field testing. Our first test system (the Los Altos Hills installation) made us aware that a check valve spring was undesirable. When the system was originally installed, there was very little circulation due to the additional flow restrictions caused by the spring. Removal of the spring seemed to correct the problem, however, and the system has been operating well for quite some time. The soft check ball was replaced with a harder rubber when it was reported that the ball sometimes got stuck in the seat.

The last real problem that we anticipate is related to the performance of the thermostatic drain. Since no device of this type has undergone significant lifetime testing, its reliability must be subject to question. Similar devices have been known to develop problems due to internal scale buildup or power pill failure. Although no such problems have been reported to date, the thermostatic drain must nevertheless be considered a questionable component until more extensive testing can be performed.

D. Conclusions

Field tests have shown that Sunspool-based freeze protection is certainly a viable and desirable alternative in thermosyphon systems. Due to the uncertain reliability of the thermostatic drain and the greater complexity of the multicomponent approach, the direct drain-down approach is probably the more desirable of the two. However, this configuration is not adaptable to packaged systems.

The truly passive photovoltaic control strategy used in conjunction with temperature sensitive snap switches appears to be more desirable from a total energy consumption standpoint, although given the current high price of PV arrays and the low power consumption of the Sunspool valve, a low voltage circuit may be more desirable from an economic standpoint. With all factors taken into consideration, field tests of the Sunspool-based thermosyphon system indicate that such systems present a competitive alternative to conventional solar assisted domestic hot water systems.

9. MARKET ASSESSMENT

Thermosyphon systems, used extensively in other countries, are slowly gaining popularity in the United States. Because of the overall cost savings of thermosyphon systems, they are expected to be used more and more in the future. However, cost-effective, energy-efficient and fail-safe freeze protection is needed for thermosyphon systems before they can be used in most of the continental U.S.

In Japan, Australia and Israel, the dominant types of solar domestic hot water heaters are based on thermosyphon techniques. In fact, 85% of the 250,000 solar systems installed in Japan in 1981 were thermosyphon systems.¹ In 1981, approximately 130,000 solar domestic hot water systems were installed in the United States.^{2,3} Thermosyphon solar hot water systems held an approximate 10% share of the solar hot water market in 1980. This market share will increase significantly over the next five years because of the cost savings associated with the pre-packaged nature of such systems.

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¹ Solar Times, November 1981.

² Frost and Sullivan, Inc., "The Market for Energy Efficient Residential Heating and Cooling Equipment and Associated Controls", 1981.

³ Hambrecht and Quist, "The Alternate Energy Industry: A Study of Technology and Investment Opportunities", 1981.

The major manufacturers of thermosyphon systems, based in Australia, seem to discount the importance of providing effective freeze protection for their systems. We attribute this to the fact that cold weather conditions in the United States are more severe than in countries where thermosyphon systems have historically been marketed. Their current method of using electrical strip heaters behind the absorber plate has not yet posed a significant marketing problem. In California, the Public Utilities Commission originally disqualified systems that used electrical means for freeze protection from its extensive rebate program. However, the restrictions were changed to allow the use of this freeze protection method in geographical areas below 1000 ft asl in altitude. As the thermosyphon systems are used in areas with more severe weather conditions, the electrical strip heater freeze protection method will have to change.

Unfortunately, the current recession and the poor financial condition of the housing market have affected the solar industry. The companies are concentrating on "weathering" the recession rather than investigating new ideas. We feel that this effect has discouraged manufacturers from pursuing freeze protection techniques significantly different from existing methods.

Our experience with the thermosyphon systems manufacturers and the solar market in general indicates that the cost will be a major factor. Therefore, the freeze protection method that replaces the current electrical heat strip heaters will have to be cost-competitive on a first-cost basis. The actuators developed under this contract

(particularly the heat motor design) can be manufactured at low enough prices compatible with the current market pressures. However, the PV-based design will be much more attractive as the cost of silicon solar cells decreases in the next five years.

10. CONCLUSIONS OF PHASE 2 INVESTIGATIONS

- The drain-down freeze protection method offers significant energy performance and system reliability advantages over the use of electric strip heaters for freeze protection of thermosyphon water heaters.
- The basic Sunspool valving mechanism can be used effectively to provide the drain-down function. The valve can be incorporated in two piping configurations compatible with discrete component and package-type thermosyphon water heaters.
- Operationally, the three alternate passive actuator mechanisms (PV design, bellows design and heat motor design) can functionally provide the actuation means for the Sunspool valving mechanism.
- Because of the cost competitive nature of the industry, the bellows and heat motor actuators are preferred for the packaged system. The PV-based actuator is preferred for the discrete component system because the valve can be placed easily in a remote area away from the solar collectors.
- The response from readers of the Solar Engineering article published as part of this contract indicates the increasingly high level of interest in thermosyphon systems in the U.S.

11. RECOMMENDATIONS FOR PHASE 3 WORK: ENGINEERING FIELD TEST

Future engineering testing should concentrate on determining the performance of the bellows and heat motor actuators in the field. Both the bellows and heat motor actuators travel characteristics will change with time. The hysteresis of the devices indicates that the frictional forces will probably affect the fill and drain operation of the system. Investigators should design the field test to determine the change in the travel characteristics of these two actuators.

The field testing program should schedule distribution of prototypes equally among original equipment manufacturers of thermosyphon equipment and active solar hot water systems and to solar contractors. When the first Sunspool valve was released, we found the feedback from both of these sources to be equally important. Also, an emphasis should be given to selecting field test sites in cold climates where freezing conditions occur during at least four months out of the year.

APPENDIX A: Overview of Freeze Protection Methods
for Active Solar/DHW Systems

APPENDIX A
OVERVIEW OF FREEZE PROTECTION METHODS FOR ACTIVE
SOLAR/DHW SYSTEMS

1. Heat Exchange Systems

A typical heat exchanger system for an active solar DHW system is shown in Figure App. 1. Heat exchange systems physically separate the collector fluid (non-freezing antifreeze), and the potable water supply. This technique is fail-safe in the event of power failure, and an necessity in areas with exceedingly poor water quality or very harsh winter weather. Heat exchange equipment adds significantly to the original system and maintenance costs, while reducing thermal performance on the order or 5-20 percent. Specially constructed tanks and expansion components are needed.

2. Pump-on Recirculation Systems

Pump-on recirculation freeze protection involves pumping hot water from solar preheat tank to the collector when freezing is imminent. The technique is relatively inexpensive, utilizing a simple storage tank and permitting direct heating of potable water in the collector (cf. Figure App. 2). However, the method has a number of serious drawbacks.

Substantial amounts of stored energy are wasted as water is circulated from the solar preheat tank to protect the collector array. More importantly, since the system depends on an electric pump for freeze protection, collectors are unprotected from freezing in the event of

Figure App. 1 Typical Heat Exchange System

Figure App. 2 Pump-on Recirculation System

electric power interruption. The lack of such a fail-safe feature in pump-on systems has been one cause of the widespread freeze damage across the country.

3. Drain-down and Drain-back

These systems drain the collector array when freezing conditions are sensed and, if properly designed, are fail-safe during power interruptions. The Sunspool valve currently marketed was developed to fill a perceived technological need in the active solar/DHW realm. The drain-down concept (cf. Figure App. 3) itself permits direct heating of the potable water, utilizes readily available and inexpensive storage tanks, minimizes system complexity and maintenance requirements, and offers significant cost advantages over heat exchange and drain-back systems.

Drain-back schemes, wherein the collector fluid returns to a reservoir when the pump turns off, involve more complex plumbing than drain-down approaches (Figure App. 4). Most require a heat exchange step or, in some cases, an air compressor to remove liquid from the collector array. Expensive, specially designed storage tanks are required, and equipment cost is even higher than that of most heat exchanger systems. Drain-back schemes also require a greater pumping power due to the lack of a continuous hydraulic loop during circulation.

Figure App. 3 Sunspool Drain-down System

Figure App. 4 Drain-back System

APPENDIX B: Solar Engineering Magazine Article:

"Drain-down Freeze Protection for Thermosyphon
Water Heaters"

Draindown freeze protection for thermosyphon water heaters

by H. T. Whitehouse

Natural market selection processes have over a period of decades strongly favored thermosyphon water heating systems in the pioneering solar countries of Australia, Japan and Israel. The dominance of thermosyphonic equipment in these markets stands as clear testimony to their inherent simplicity, low cost and excellent thermal performance. And, while their widespread adoption in these areas can be partly attributed to unique climatological, sociological or technical factors, it is quite plausible that history will repeat itself as the solar market in the United States matures. The process is already being accelerated by the aggressive marketing of Australian (Shell/Solahart), Japanese (Yazaki) and Israeli (Amcor) thermosyphonic equipment in the continental U.S.

Presently, there are several barriers to widespread adoption of thermosyphon systems in the United States. Perhaps foremost is the relatively meager experiential base shared by those in the solar industry and the end user community. To date, solar water heater designers in the United States have almost unanimously opted for technically intensive solutions employing active controls.

Geometric constraints imposed by the physics of thermosyphon systems represent another significant barrier to market acceptance. Because the solar storage tank must be placed above the collector array to insure thermosyphon circulation, and because the most logical collector position for maximum solar access is generally a roof structure, one invariably ends up with a heavy cylindrical storage tank in or on the roof. This situation poses both aesthetic and structural problems.

There is yet another obstacle in the way of widespread adoption of most thermosyphon systems—the absence of a fail-safe method of collector freeze protection. Ironically, thermosyphon systems are especially susceptible to debilitating collector freeze damage since they lack even the most rudimentary protective controls.

This article discusses the thermal mechanisms of collector freezing and describes a simple extension of active draindown freeze protection technology which can be applied to thermosyphonic systems.

Radiation losses to the night sky

Quite commonly, designers and installers gauge the potential for collector freeze damage in a given locale by reviewing the historical records of measured air temperature. The reasoning

is that no freeze protection apparatus will be necessary if the recorded extremes seldom, if ever, fall below 32°F. This seemingly logical line of reasoning is very much in error.

The missing element is radiation heat transfer—an often misunderstood and in this case underestimated factor in collector freezing events. Paradoxically, radiation losses to a cloudless night sky can depress the temperature of an absorber plate by 10°F or more below the surrounding air temperature. Thus a mild 40°F night can set the stage for a disastrous freeze.

This subtle yet effective night sky radiation heat loss phenomenon is evident elsewhere in our surroundings. For instance on an early fall morning you may have noticed what appear to be shadows under trees, tables and other objects on an otherwise open, frost-covered field. This is caused by selective freezing of beads of dew which form on the grass. Those beads which have been optically exposed to the clear night sky will preferentially freeze and give the appearance of frost, and those shielded from radiation losses by, say, a table, will not freeze. Importantly, this freeze-based patterning can develop even if the air temperature remains above 32°F all evening.

A parked car is another excellent example. In proper weather conditions, dew will begin to form on the body in the late evening. The dew forms when warm, moist air comes in contact with the cooler surfaces of the automobile. You may recall that the uppermost surfaces—those facing the sky—typically are the first to show the dew droplets. This is because these surfaces are preferentially cooled by radiation losses to the sky. In contrast, the sides of the automobile are in radiant communication with nearby buildings, the ground and other mass elements which still retain the day's heat. This radiant environment serves to keep the sides of the car warm and in a relative sense delays the formation of dew droplets.

Examples aside, the fact remains that collector freeze protection is a major issue in most—if not all—of the continental United States. Due to night sky radiant effects, air temperature statistics used alone severely underestimate the collector freeze potential of a given area. This oversight has repeatedly proven to be disastrous, as evidenced by the extensive solar equipment freezes in Los Angeles in the early 1900's, the recurrent system damage in Florida in the 1940's and the widespread freezups throughout Florida, Arizona, Colorado and California in recent years.

(continued)

Radiation losses as they affect a collector

Roof-mounted collector arrays in a clear evening environment typically have an unobstructed view of the sky dome. On a cloudless evening, the sky will have an effective temperature (Ref. 1) given approximately by:

$$T_{sky} = .0411 (T_{air})^{1.5}$$

where

T_{sky} and T_{air} are in absolute Rankine degrees (°R).

The effect of water vapor in the air has been neglected in this correlation, but this omission is acceptable in the drier winter months (Ref. 2). The correlation predicts that the sky dome will have a substantially lower temperature than the surrounding air temperature. Using our previous example of a 40°F (4.5°C) air temperature, we find T_{sky} to be slightly less than 0°F (−18°C).

The effective sky temperature can be used to compute the equilibrium, nighttime absorber plate temperature. While a thorough quantitative analysis is beyond the scope of this article, it is revealing to qualitatively examine the key energy flows in the collector as illustrated by Figure 1. Here principal heat flow interactions between the glazing, the night sky, surrounding air and collector absorber plate are superimposed on a typical collector cross section.

Because the loss related radiation heat flows are in the infrared spectrum, the collector cover glass appears opaque to this radiation. Accordingly, the only energy transmitted through the glass is that conducted. For all practical purposes, the conduction resistance in a single glazed collector is small, so one can assume that the inside and outside surfaces of the glazing are at approximately the same temperature.

The equilibrium temperature reached by the glass depends upon the relative rates at which energy is lost and gained at the glass surfaces. On a clear evening, the outside surface of the glazing will be losing energy to the night sky (Q_{sky}). Unfortunately, this radiation loss is encouraged by the high emissivity of glass in the infrared wavelengths. Simultaneously the outside glass surface will be gaining energy from the surrounding air molecules in an attempt to compensate for the radiation losses to the sky. Finally the inside surface of the glazing will be receiving energy from the absorber plate (Q_{loss}) by radiation and convection.

As time passes and the absorber plate cools, the energy flows eventually cause the glass temperature to seek a level between the surrounding air temperature and the night sky temperature. A breezy evening will result in a glass temperature closer to the surrounding air temperature, since the moving air will increase the convective coupling to the glass and enhance gains. In contrast, a still evening will tend to drive the glazing closer to the night sky temperature since the radiation losses will dominate.

As the glass temperature gravitates to equilibrium in its radiation/convective environment, the absorber plate temperature follows suit. This is because the absorber sees only the inside glass surface in its thermal communication—the colder the glass surface, the colder the absorber plate. And, while the rates of energy flow involved are generally low, the non-circulating collector has only its low effective thermal mass to resist this cooling process. The absorber plate temperature is thus inexorably drawn towards the glass temperature, which itself is at the mercy of the radiant environment of the night sky.

Figure 3. Multicomponent draindown approach.

Thus, on a cloudless evening, we will eventually find the glazing and absorber plate at a lower temperature than the surrounding air. This cooling process can be slowed by employing double glazing on the panels, and/or by utilizing a selective surface coating on the absorber plate. The selective surface with a purposely low emissivity in the infrared reduces the rate of radiant energy transfer between the absorber plate and inside surface of the glass.

Methods of collector freeze protection

The available methods of collector freeze protection in solar domestic hot water systems have been admirably covered in recent literature (Ref. 3).

Briefly, these methods include:

- pump recirculation methods;
- heat exchanger/anti freeze systems;
- drainback methods;
- draindown methods;
- electrical resistance heating.

Due to the absence of a pump and controller, thermosyphon systems obviously cannot employ pump recirculation methodology. Anti freeze solutions often introduce increased fluid viscosity—a factor which can affect the delicate flows nurtured by the thermosyphon potential. Heat exchanger systems also add substantially to the cost and complexity of the system and degrade thermal performance significantly due to the lack of forced circulation on either side of the heat exchanger surface. Electrical resistance heaters are, at minimum, a questionable appropriation of high quality energy resources and provide no protection in the not-so-unlikely event of coincident power failure and low ambient temperatures. Drainback methods suffer most of the hardware disadvantages of heat exchange systems, are further complicated by the geometric constraints of thermosyphon systems and require the use of some form of pumping device.

This process of elimination led to the consideration of a draindown approach for thermosyphon freeze protection. The draindown approach is premised on the direct control of pressurized potable water by the appropriate hardware. In the shut-off or drain mode, all collectors and exposed piping are completely devoid of water. In the operate or fill mode, potable wa-

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ter is heated directly and circulated by the thermosyphon potential. Due to the nature of available valving hardware, such a system can easily be made fail-safe in the event of a power failure.

Draindown freeze protection for active systems

To better appreciate the special requirements of a draindown thermosyphon water heater, it is helpful to review draindown techniques as they apply to active systems. Figure 2 presents an isometric of a typical active solar water heater employing draindown freeze protection. The draindown valve is interposed between the pressurized preheat tank and the collector array. Whenever power is removed from the valve, the city water pressure is isolated from the collector array, and draining commences through a dedicated port of the valve.

Naturally the draindown valve must be installed in an area protected from freezing temperatures. In an active system, the valve is typically located in a utility room, basement or garage area adjacent to the storage tank, pump and controller. The collectors, most often mounted on the roof, drain down into this protected area—usually into a service sink or other sanitary drain. The amount of water drained is typically on the order of one gallon.

It is important to note that the integral draindown valve in an active system serves two distinct functions at a single point in the piping system. It first isolates the array from the pressurized water and then serves as the point of drainage.

Draindown techniques for thermosyphon systems

Figures 3 and 4 illustrate two possible piping arrangements for a draindown thermosyphon water heater. In each case, in order to evacuate the water from the collectors and exposed

Figure 4. Modified three-port Sunspool valve arrangement.

piping, one must again isolate the city water pressure. This generally calls for some form of valving mechanism between the tank and the collector array. To complete the task, a path for the water drainage must be provided. Naturally one must locate this draining point opening below the collector array. Thus the functions of pressure isolation and draining must be carried out by distinct and physically separated hardware elements. It is

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Typical examples of our solar collector designs

Figure 5. Cross section of standard Sunspool valve.

here that thermosyphon draindown systems depart from their active counterparts.

Figure 3 illustrates a multi-component approach to the problem using a standard Sunspool draindown valve with a thermostatically-actuated, single port valve positioned at the bottom of the array. The draindown valve, a cross-section of which is shown in Figure 5, is mounted in an inverted position in a thermally protected area close to the storage tank. In this configuration, the valve port normally used for draining becomes a

point of air admission during the drain cycle. The independent single port valve is thermostatically controlled to open after the draindown valve completes the pressure isolation task. When the single port valve opens, only the small amount of water in the collectors and exposed piping flows over the roof surface.

When warmer ambient conditions return, the draindown valve begins filling both the supply and return lines of the array. When this relatively warm water comes in contact with the thermostatic element of the single port valve, it quickly closes.

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A second plumbing arrangement is depicted in Figure 4. Here the collector supply and return lines are routed into a protected attic or crawl space. At the low point of the piping—purposely below the lowest portion of the collector array—a modified Sunspool valve is operated as a simple three port device. The remaining two ports of the standard Sunspool valve become a sensitive check valve positioned in the collector return line inside the protected area. A standard air vent/vacuum breaker combination is included for air elimination during fill and vacuum relief during drain.

When the modified draindown valve in Figure 4 is energized, it admits pressurized water into the collector supply piping, automatically filling the collector array and associated piping. The air vent automatically eliminates the displaced air. The check valve then permits normal thermosyphon flow, while preventing reverse thermosyphon flow on those occasions when the collector temperature is below the tank temperature, and yet draining has not occurred.

When deenergized, the draindown valve isolates the tank pressure and connects the collector piping to the integral drain port. The pressure reduction in the collector array causes the check valve to firmly seat and isolate the return line. The vacuum breaker admits air during the draining process.

Both plumbing configurations have been constructed and are in operation. The configuration shown in Figure 3 has successfully operated under field conditions through the winter of 1980-81 in a northern California climate. The Figure 4 configuration is located at Sunspool headquarters and has been functioning since March 1981.

Both of the design concepts described above require some

form of valve actuation for the necessary fill and drain operations. The most obvious powering and control strategy for the thermosyphon draindown valve employs a low voltage transformer and a thermostatic switch. A second, more self-sufficient approach uses a 7 to 10 watt photovoltaic array to power a 12 volt version of the Sunspool valve driver. In this arrangement, the valve is de-energized and returned to the drain position every evening. A third approach under investigation eliminates all electrical components. A refrigerant-filled sensing bulb located in the collector monitors temperature and transmits a corresponding pressure to actuating bellows by means of a capillary tube.

The future

Sunspool plans to continue research and development efforts on the two principal plumbing configurations and the various control/powering strategies. Additional field test installations are being established for the 1981-82 winter season, and an extensive computerized data logging system will continue to monitor the factory test facilities.

Costsharing and programming support for the project has been received from DOE's Marketable Products for Passive Solar Applications Program, managed by the Chicago Regional Office of the U.S. Department of Energy.

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APPENDIX C: Computer Printout of Thermosyphon
System Performance

Appendix C Computer Printout of Thermosyphon System Performance

Channel

- 0 Ambient Air Temperature (F)
- 1 Collector Inlet Temperature
- 2 Collector Outlet Temperature
- 3 Tank Top Temperature
- 4 Insolation (Btu/hr-ft²)
- 5 Fill/drain Indicator (3.1 V for Drain, 0 V for Fill)
- 6 PV array Voltage (V)

081:00:00:00	0	47.6°F	1	46.4°F	2	44.2°F	3	80.4°F	4	0.0000BTU	5	3.122 V	6	0.012 V
081:00:05:00	0	47.2°F	1	46.5°F	2	44.4°F	3	80.5°F	4	0.0000BTU	5	3.122 V	6	0.012 V
081:00:10:00	0	46.9°F	1	46.4°F	2	44.2°F	3	80.4°F	4	0.0000BTU	5	3.122 V	6	0.012 V
081:00:15:00	0	47.0°F	1	46.5°F	2	44.2°F	3	80.5°F	4	0.0000BTU	5	3.122 V	6	0.013 V
081:00:20:00	0	46.9°F	1	46.5°F	2	44.2°F	3	80.5°F	4	0.0000BTU	5	3.122 V	6	0.013 V
081:00:25:00	0	46.5°F	1	46.4°F	2	44.1°F	3	80.3°F	4	0.0000BTU	5	3.123 V	6	0.013 V
081:00:30:00	0	46.4°F	1	45.2°F	2	44.0°F	3	80.4°F	4	0.3436BTU	5	3.122 V	6	0.013 V
081:00:35:00	0	46.3°F	1	46.2°F	2	43.8°F	3	80.4°F	4	0.3436BTU	5	3.121 V	6	0.012 V
081:00:40:00	0	46.0°F	1	45.9°F	2	43.7°F	3	80.3°F	4	0.0000BTU	5	3.122 V	6	0.013 V
081:00:45:00	0	45.9°F	1	45.8°F	2	43.7°F	3	80.2°F	4	0.0859BTU	5	3.122 V	6	0.013 V
081:00:50:00	0	46.1°F	1	45.7°F	2	43.8°F	3	80.3°F	4	0.0000BTU	5	3.122 V	6	0.013 V
081:00:55:00	0	46.2°F	1	45.7°F	2	43.6°F	3	80.2°F	4	0.0000BTU	5	3.122 V	6	0.012 V
081:01:00:00	0	45.7°F	1	45.6°F	2	43.5°F	3	80.1°F	4	0.6872BTU	5	3.122 V	6	0.012 V
081:01:05:00	0	45.5°F	1	45.4°F	2	43.3°F	3	80.1°F	4	0.0000BTU	5	3.123 V	6	0.013 V
081:01:10:00	0	45.3°F	1	45.0°F	2	43.3°F	3	80.0°F	4	0.0000BTU	5	3.122 V	6	0.012 V
081:01:15:00	0	45.3°F	1	45.0°F	2	43.1°F	3	80.0°F	4	0.0000BTU	5	3.122 V	6	0.012 V
081:01:20:00	0	45.2°F	1	44.9°F	2	42.8°F	3	80.1°F	4	0.3436BTU	5	3.122 V	6	0.013 V

081:01:25:00 0 45.2°F	1	44.7°F	2	42.6°F	3	80.0°F	4-0.0859BTU	5	3.122 V	6	0.012 V
081:01:30:00 0 44.9°F	1	44.5°F	2	42.5°F	3	80.0°F	4 0.0000BTU	5	3.122 V	6	0.013 V
081:01:35:00 0 44.9°F	1	44.4°F	2	42.3°F	3	80.0°F	4-0.0859BTU	5	3.122 V	6	0.012 V
081:01:40:00 0 44.9°F	1	44.4°F	2	42.2°F	3	79.9°F	4 0.3436BTU	5	3.122 V	6	0.013 V
081:01:45:00 0 44.7°F	1	44.1°F	2	42.1°F	3	79.6°F	4 0.5154BTU	5	3.122 V	6	0.013 V
081:01:50:00 0 44.9°F	1	44.2°F	2	42.3°F	3	79.8°F	4 0.0000BTU	5	3.122 V	6	0.013 V
081:01:55:00 0 44.7°F	1	44.2°F	2	42.4°F	3	79.7°F	4 0.0000BTU	5	3.122 V	6	0.013 V
081:02:00:00 0 44.8°F	1	44.2°F	2	42.2°F	3	79.7°F	4 0.0000BTU	5	3.122 V	6	0.013 V
081:02:05:00 0 44.6°F	1	44.1°F	2	42.2°F	3	79.7°F	4-0.2577BTU	5	3.123 V	6	0.013 V
081:02:10:00 0 44.5°F	1	44.0°F	2	42.0°F	3	79.7°F	4 0.0000BTU	5	3.123 V	6	0.013 V
081:02:15:00 0 44.4°F	1	43.8°F	2	41.9°F	3	79.5°F	4 0.0000BTU	5	3.122 V	6	0.012 V
081:02:20:00 0 44.4°F	1	43.7°F	2	41.8°F	3	79.5°F	4 0.0000BTU	5	3.122 V	6	0.012 V
081:02:25:00 0 44.3°F	1	43.7°F	2	41.7°F	3	79.5°F	4 0.0000BTU	5	3.122 V	6	0.013 V
081:02:30:00 0 44.3°F	1	43.6°F	2	41.7°F	3	79.5°F	4 0.0000BTU	5	3.122 V	6	0.013 V
081:02:35:00 0 44.3°F	1	43.6°F	2	41.6°F	3	79.4°F	4 0.0000BTU	5	3.122 V	6	0.013 V
081:02:40:00 0 44.3°F	1	43.5°F	2	41.5°F	3	79.4°F	4 0.0000BTU	5	3.122 V	6	0.013 V
081:02:45:00 0 44.1°F	1	43.3°F	2	41.4°F	3	79.3°F	4 0.0000BTU	5	3.122 V	6	0.012 V
081:02:50:00 0 44.0°F	1	43.3°F	2	41.4°F	3	79.2°F	4 0.0000BTU	5	3.122 V	6	0.012 V
081:02:55:00 0 44.8°F	1	43.4°F	2	41.5°F	3	79.4°F	4 0.0000BTU	5	3.123 V	6	0.013 V
081:03:00:00 0 44.2°F	1	43.4°F	2	41.3°F	3	79.2°F	4 0.0000BTU	5	3.122 V	6	0.012 V
081:03:05:00 0 44.2°F	1	43.3°F	2	41.4°F	3	79.1°F	4 0.0000BTU	5	3.122 V	6	0.012 V
081:03:10:00 0 44.2°F	1	43.3°F	2	41.3°F	3	79.1°F	4 0.0000BTU	5	3.122 V	6	0.012 V

081:03:15:00 0 44.2°F	1	43.3°F	2	41.3°F	3	79.0°F	4	0.0000BTU	5	3.121 V	6	0.012 V
081:03:20:00 0 44.1°F	1	43.4°F	2	41.3°F	3	79.1°F	4	0.0000BTU	5	3.122 V	6	0.013 V
081:03:25:00 0 43.9°F	1	43.2°F	2	41.3°F	3	79.0°F	4	0.0000BTU	5	3.122 V	6	0.012 V
081:03:30:00 0 44.0°F	1	43.3°F	2	41.3°F	3	79.0°F	4	0.0000BTU	5	3.122 V	6	0.012 V
081:03:35:00 0 43.9°F	1	43.2°F	2	41.3°F	3	78.9°F	4	0.0000BTU	5	3.121 V	6	0.011 V
081:03:40:00 0 44.1°F	1	43.2°F	2	41.1°F	3	78.9°F	4	0.0000BTU	5	3.123 V	6	0.013 V
081:03:45:00 0 44.3°F	1	43.2°F	2	41.2°F	3	78.9°F	4	0.0000BTU	5	3.123 V	6	0.013 V
081:03:50:00 0 43.8°F	1	43.2°F	2	41.3°F	3	78.8°F	4	0.0000BTU	5	3.123 V	6	0.013 V
081:03:55:00 0 43.2°F	1	43.0°F	2	41.0°F	3	78.7°F	4	-0.3436BTU	5	3.122 V	6	0.012 V
081:04:00:00 0 42.7°F	1	42.8°F	2	40.6°F	3	78.7°F	4	-0.6872BTU	5	3.122 V	6	0.013 V
081:04:05:00 0 42.5°F	1	42.6°F	2	40.3°F	3	78.7°F	4	-0.6872BTU	5	3.122 V	6	0.013 V
081:04:10:00 0 42.4°F	1	42.5°F	2	40.0°F	3	78.7°F	4	-0.4295BTU	5	3.122 V	6	0.013 V
081:04:15:00 0 42.4°F	1	42.2°F	2	39.8°F	3	78.7°F	4	-0.5154BTU	5	3.122 V	6	0.012 V
081:04:20:00 0 42.3°F	1	42.2°F	2	39.7°F	3	78.7°F	4	-0.1718BTU	5	3.122 V	6	0.012 V
081:04:25:00 0 42.0°F	1	41.9°F	2	39.4°F	3	78.5°F	4	0.0000BTU	5	3.122 V	6	0.012 V
081:04:30:00 0 42.4°F	1	41.9°F	2	39.2°F	3	78.6°F	4	-0.0859BTU	5	3.122 V	6	0.012 V
081:04:35:00 0 42.2°F	1	41.8°F	2	39.1°F	3	78.5°F	4	-0.1718BTU	5	3.122 V	6	0.012 V
081:04:40:00 0 42.0°F	1	41.7°F	2	39.0°F	3	78.6°F	4	0.0000BTU	5	3.122 V	6	0.013 V
081:04:45:00 0 41.7°F	1	41.5°F	2	38.9°F	3	78.5°F	4	-0.1718BTU	5	3.123 V	6	0.013 V
081:04:50:00 0 41.7°F	1	41.3°F	2	38.7°F	3	78.5°F	4	-0.2377BTU	5	3.122 V	6	0.012 V
081:04:55:00 0 41.5°F	1	41.2°F	2	38.5°F	3	78.3°F	4	-0.1718BTU	5	3.123 V	6	0.013 V
081:05:00:00 0 41.5°F	1	41.1°F	2	38.5°F	3	78.3°F	4	-0.0859BTU	5	3.122 V	6	0.012 V

081:05:05:00 0 41.3°F	1	41.0°F	2	38.4°F	3	78.2°F	4-0.0859BTU	5	3.123 V	6	0.013 V
081:05:10:00 0 41.7°F	1	40.8°F	2	38.3°F	3	78.3°F	4 0.0000BTU	5	3.122 V	6	0.012 V
081:05:15:00 0 41.6°F	1	40.8°F	2	38.2°F	3	78.2°F	4 0.0000BTU	5	3.123 V	6	0.013 V
081:05:20:00 0 41.1°F	1	40.7°F	2	38.1°F	3	78.2°F	4 0.0000BTU	5	3.122 V	6	0.012 V
081:05:25:00 0 41.6°F	1	40.6°F	2	38.2°F	3	78.1°F	4 0.0000BTU	5	3.122 V	6	0.012 V
081:05:30:00 0 41.3°F	1	40.5°F	2	38.0°F	3	78.1°F	4 0.0000BTU	5	3.123 V	6	0.012 V
081:05:35:00 0 41.1°F	1	40.4°F	2	37.9°F	3	78.1°F	4 0.0000BTU	5	3.123 V	6	0.013 V
081:05:40:00 0 41.3°F	1	40.5°F	2	37.8°F	3	78.0°F	4 0.0000BTU	5	3.123 V	6	0.013 V
081:05:45:00 0 41.3°F	1	40.3°F	2	37.8°F	3	78.0°F	4 0.0000BTU	5	3.122 V	6	0.013 V
081:05:50:00 0 41.3°F	1	40.3°F	2	37.7°F	3	77.9°F	4 0.0000BTU	5	3.122 V	6	0.013 V
081:05:55:00 0 41.3°F	1	40.3°F	2	37.8°F	3	78.0°F	4-0.2577BTU	5	3.123 V	6	0.015 V
081:06:00:00 0 41.0°F	1	40.1°F	2	37.6°F	3	77.8°F	4 0.0000BTU	5	3.123 V	6	0.020 V
081:06:05:00 0 41.3°F	1	40.2°F	2	37.7°F	3	77.9°F	4 0.1718BTU	5	3.122 V	6	0.031 V
081:06:10:00 0 41.3°F	1	40.2°F	2	37.6°F	3	77.8°F	4 0.6872BTU	5	3.123 V	6	0.050 V
081:06:15:00 0 41.3°F	1	40.3°F	2	37.8°F	3	77.7°F	4 1.1167BTU	5	3.123 V	6	0.078 V
081:06:20:00 0 41.2°F	1	40.1°F	2	37.7°F	3	77.6°F	4 1.9757BTU	5	3.122 V	6	0.115 V
081:06:25:00 0 41.4°F	1	40.3°F	2	38.0°F	3	77.7°F	4 2.4911BTU	5	3.122 V	6	0.155 V
081:06:30:00 0 41.5°F	1	40.3°F	2	38.1°F	3	77.6°F	4 3.350BTU	5	3.123 V	6	0.193 V
081:06:35:00 0 41.6°F	1	40.4°F	2	38.4°F	3	77.6°F	4 4.123BTU	5	3.122 V	6	0.239 V
081:06:40:00 0 42.0°F	1	40.5°F	2	38.8°F	3	77.6°F	4 4.982BTU	5	3.122 V	6	0.280 V
081:06:45:00 0 42.4°F	1	40.7°F	2	39.3°F	3	77.5°F	4 6.098BTU	5	3.122 V	6	0.325 V
081:06:50:00 0 42.7°F	1	41.1°F	2	39.8°F	3	77.5°F	4 6.957BTU	5	3.122 V	6	0.360 V

081:06:55:00 0 42.8°F	1	41.4°F	2	40.5°F	3	77.4°F	4	7.816BTU	5	3.122 V	6	0.399 V
081:07:00:00 0 43.3°F	1	41.9°F	2	41.1°F	3	77.5°F	4	8.332BTU	5	3.122 V	6	0.431 V
081:07:05:00 0 43.7°F	1	42.2°F	2	41.7°F	3	77.4°F	4	9.019BTU	5	3.122 V	6	0.460 V
081:07:10:00 0 44.7°F	1	42.7°F	2	42.4°F	3	73.8°F	4	9.706BTU	5	3.122 V	6	0.490 V
081:07:15:00 0 45.1°F	1	43.2°F	2	42.9°F	3	68.8°F	4	10.136BTU	5	3.122 V	6	0.517 V
081:07:20:00 0 45.4°F	1	43.5°F	2	43.5°F	3	66.6°F	4	10.737BTU	5	3.122 V	6	0.538 V
081:07:25:00 0 45.8°F	1	44.1°F	2	44.4°F	3	66.7°F	4	11.510BTU	5	3.122 V	6	0.561 V
081:07:30:00 0 45.9°F	1	44.5°F	2	44.9°F	3	66.7°F	4	11.854BTU	5	3.122 V	6	0.585 V
081:07:35:00 0 46.2°F	1	45.0°F	2	45.6°F	3	66.6°F	4	12.111BTU	5	3.122 V	6	0.607 V
081:07:40:00 0 46.8°F	1	45.7°F	2	46.4°F	3	66.5°F	4	12.369BTU	5	3.123 V	6	0.628 V
081:07:45:00 0 47.0°F	1	46.1°F	2	47.1°F	3	66.5°F	4	12.541BTU	5	3.122 V	6	0.649 V
081:07:50:00 0 47.6°F	1	46.6°F	2	47.7°F	3	66.6°F	4	12.970BTU	5	3.122 V	6	0.677 V
081:07:55:00 0 47.9°F	1	47.1°F	2	48.3°F	3	66.5°F	4	13.400BTU	5	3.122 V	6	0.696 V
081:08:00:00 0 48.3°F	1	47.7°F	2	49.0°F	3	66.6°F	4	13.572BTU	5	3.122 V	6	0.716 V
081:08:05:00 0 48.5°F	1	48.1°F	2	49.5°F	3	66.6°F	4	14.001BTU	5	3.123 V	6	0.751 V
081:08:10:00 0 48.8°F	1	48.6°F	2	50.2°F	3	66.6°F	4	15.891BTU	5	3.123 V	6	0.793 V
081:08:15:00 0 49.2°F	1	49.2°F	2	53.0°F	3	66.5°F	4	18.468BTU	5	3.122 V	6	0.893 V
081:08:20:00 0 49.3°F	1	49.8°F	2	56.6°F	3	66.7°F	4	18.554BTU	5	3.122 V	6	1.059 V
081:08:25:00 0 49.7°F	1	52.3°F	2	58.7°F	3	66.8°F	4	19.499BTU	5	3.122 V	6	1.252 V
081:08:30:00 0 50.1°F	1	55.7°F	2	60.6°F	3	66.8°F	4	20.358BTU	5	3.122 V	6	1.469 V
081:08:35:00 0 50.6°F	1	59.6°F	2	62.1°F	3	66.8°F	4	21.990BTU	5	3.123 V	6	1.709 V
081:08:40:00 0 51.1°F	1	61.4°F	2	62.9°F	3	66.8°F	4	21.560BTU	5	3.122 V	6	1.969 V

081:03:45:00 0 52.0°F	1	63.5°F	2	63.8°F	3	66.7°F	4	21.217RTU	5	3.122 V	6	2.247 V
081:03:50:00 0 51.5°F	1	65.2°F	2	64.0°F	3	66.7°F	4	19.241RTU	5	3.122 V	6	2.515 V
081:03:55:00 0 51.9°F	1	66.2°F	2	64.5°F	3	66.8°F	4	15.290RTU	5	3.122 V	6	2.798 V
081:09:00:00 0 52.2°F	1	67.7°F	2	64.1°F	3	66.7°F	4	15.032RTU	5	3.122 V	6	3.091 V
081:09:05:00 0 52.7°F	1	69.2°F	2	63.3°F	3	66.7°F	4	15.547RTU	5	3.122 V	6	3.377 V
081:09:10:00 0 54.1°F	1	70.0°F	2	62.7°F	3	66.8°F	4	16.321RTU	5	3.122 V	6	0 V/
A081:09:15:00 0 53.8°F	1	70.8°F	2	63.7°F	3	66.7°F	4	16.321RTU	5	3.122 V	6	0 V/
A081:09:20:00 0 57.4°F	1	71.3°F	2	64.8°F	3	66.7°F	4	20.014RTU	5	3.122 V	6	4.228 V
081:09:25:00 0 63.5°F	1	72.1°F	2	66.7°F	3	66.8°F	4	21.389RTU	5	3.122 V	6	4.556 V
081:09:30:00 0 61.1°F	1	71.8°F	2	68.5°F	3	66.7°F	4	21.389RTU	5	3.122 V	6	4.826 V
081:09:35:00 0 56.8°F	1	71.4°F	2	71.9°F	3	66.7°F	4	34.87RTU	5	3.122 V	6	5.116 V
081:09:40:00 0 57.7°F	1	71.2°F	2	74.5°F	3	66.7°F	4	100.93RTU	5	3.122 V	6	5.353 V
081:09:45:00 0 57.9°F	1	70.8°F	2	78.8°F	3	66.8°F	4	103.33RTU	5	3.121 V	6	5.624 V
081:09:50:00 0 58.4°F	1	70.0°F	2	81.7°F	3	66.9°F	4	109.00RTU	5	3.122 V	6	6.009 V
081:09:55:00 0 60.1°F	1	70.3°F	2	85.1°F	3	67.0°F	4	113.55RTU	5	3.122 V	6	6.334 V
081:10:00:00 0 59.8°F	1	70.0°F	2	88.4°F	3	66.8°F	4	118.02RTU	5	3.122 V	6	6.630 V
081:10:05:00 0 59.0°F	1	69.8°F	2	90.9°F	3	67.0°F	4	122.83RTU	5	3.122 V	6	6.950 V
081:10:10:00 0 60.8°F	1	69.3°F	2	92.4°F	3	66.9°F	4	128.33RTU	5	3.122 V	6	7.220 V
081:10:15:00 0 60.0°F	1	69.8°F	2	93.8°F	3	67.0°F	4	135.89RTU	5	3.122 V	6	7.572 V
081:10:20:00 0 61.1°F	1	65.0°F	2	129.9°F	3	68.2°F	4	142.67RTU	5	0.018 V	6	0 V/
A081:10:25:00 0 60.9°F	1	65.8°F	2	117.7°F	3	68.6°F	4	148.60RTU	5	0.019 V	6	0 V/
A081:10:30:00 0 62.7°F	1	65.8°F	2	117.0°F	3	71.7°F	4	153.41RTU	5	0.019 V	6	8.412 V

081:10:35:00 0 62.2°F	1 65.7°F	2 117.2°F	3 72.8°F	4 157.62BTU	5 0.019 V	6 8.684 V
081:10:40:00 0 63.3°F	1 65.8°F	2 117.5°F	3 73.5°F	4 163.21BTU	5 0.019 V	6 8.836 V
081:10:45:00 0 63.0°F	1 65.7°F	2 117.8°F	3 74.4°F	4 167.59BTU	5 0.019 V	6 9.133 V
081:10:50:00 0 63.1°F	1 66.0°F	2 118.8°F	3 75.7°F	4 171.71BTU	5 0.018 V	6 9.311 V
081:10:55:00 0 62.8°F	1 66.0°F	2 119.6°F	3 76.7°F	4 175.40BTU	5 0.019 V	6 0 V/
A081:11:00:00 0 64.6°F	1 66.0°F	2 120.3°F	3 77.6°F	4 184.42BTU	5 0.019 V	6 9.853 V
081:11:05:00 0 65.9°F	1 66.1°F	2 121.4°F	3 78.7°F	4 187.77BTU	5 0.020 V	6 0 V/
A081:11:10:00 0 64.2°F	1 66.1°F	2 122.0°F	3 79.7°F	4 192.50BTU	5 0.020 V	6 0 V/
A081:11:15:00 0 64.8°F	1 66.2°F	2 122.7°F	3 80.8°F	4 197.74BTU	5 0.019 V	6 10.375 V
081:11:20:00 0 65.0°F	1 66.2°F	2 123.9°F	3 81.9°F	4 204.09BTU	5 0.020 V	6 0 V/
A081:11:25:00 0 65.1°F	1 66.2°F	2 124.9°F	3 83.0°F	4 213.89BTU	5 0.020 V	6 0 V/
A081:11:30:00 0 65.9°F	1 66.2°F	2 125.5°F	3 84.1°F	4 215.35BTU	5 0.020 V	6 0 V/
A081:11:35:00 0 65.1°F	1 66.3°F	2 126.4°F	3 85.3°F	4 219.64BTU	5 0.020 V	6 11.157 V
081:11:40:00 0 66.0°F	1 66.5°F	2 127.0°F	3 86.4°F	4 223.94BTU	5 0.020 V	6 0 V/
A081:11:45:00 0 66.0°F	1 66.6°F	2 127.8°F	3 87.4°F	4 229.26BTU	5 0.020 V	6 0 V/
A081:11:50:00 0 66.4°F	1 66.4°F	2 128.3°F	3 88.4°F	4 233.81BTU	5 0.021 V	6 11.715 V
081:11:55:00 0 66.8°F	1 66.6°F	2 129.2°F	3 89.6°F	4 237.42BTU	5 0.020 V	6 0 V/
A081:12:00:00 0 67.7°F	1 66.6°F	2 129.7°F	3 90.6°F	4 241.72BTU	5 0.020 V	6 0 V/
A081:12:05:00 0 67.9°F	1 66.9°F	2 130.5°F	3 91.6°F	4 251.51BTU	5 0.021 V	6 0 V/
A081:12:10:00 0 67.9°F	1 67.0°F	2 131.0°F	3 92.9°F	4 252.80BTU	5 0.021 V	6 0 V/
A081:12:15:00 0 68.4°F	1 67.1°F	2 131.7°F	3 93.9°F	4 256.84BTU	5 0.021 V	6 0 V/
A081:12:20:00 0 67.2°F	1 67.2°F	2 132.5°F	3 94.9°F	4 259.16BTU	5 0.021 V	6 0 V/

A081:12:25:00 0 68.6°F	1	67.4°F	2	133.2°F	3	96.2°F	4	265.34BTU	5	0.021 V	6	0 V/
A081:12:30:00 0 67.7°F	1	67.4°F	2	133.7°F	3	96.9°F	4	268.17BTU	5	0.021 V	6	0 V/
A081:12:35:00 0 66.7°F	1	67.7°F	2	134.0°F	3	97.8°F	4	268.09BTU	5	0.022 V	6	0 V/
A081:12:40:00 0 68.2°F	1	68.2°F	2	134.3°F	3	98.9°F	4	271.70BTU	5	0.021 V	6	0 V/
A081:12:45:00 0 67.5°F	1	68.7°F	2	134.9°F	3	99.9°F	4	276.51BTU	5	0.022 V	6	0 V/
A081:12:50:00 0 68.4°F	1	69.1°F	2	135.4°F	3	100.7°F	4	276.42BTU	5	0.022 V	6	0 V/
A081:12:55:00 0 67.7°F	1	69.6°F	2	135.9°F	3	101.8°F	4	279.17BTU	5	0.022 V	6	0 V/
A081:13:00:00 0 66.4°F	1	70.1°F	2	136.4°F	3	102.6°F	4	280.03BTU	5	0.022 V	6	0 V/
A081:13:05:00 0 67.0°F	1	70.6°F	2	137.1°F	3	103.6°F	4	282.78BTU	5	0.022 V	6	0 V/
A081:13:10:00 0 67.6°F	1	71.4°F	2	137.3°F	3	104.6°F	4	285.96BTU	5	0.022 V	6	0 V/
A081:13:15:00 0 67.7°F	1	72.0°F	2	137.8°F	3	105.2°F	4	283.55BTU	5	0.022 V	6	0 V/
A081:13:20:00 0 67.0°F	1	72.6°F	2	138.2°F	3	106.0°F	4	284.75BTU	5	0.022 V	6	0 V/
A081:13:25:00 0 67.5°F	1	73.5°F	2	138.7°F	3	107.0°F	4	287.85BTU	5	0.023 V	6	0 V/
A081:13:30:00 0 67.5°F	1	74.3°F	2	139.3°F	3	107.9°F	4	289.13BTU	5	0.023 V	6	0 V/
A081:13:35:00 0 67.0°F	1	75.0°F	2	139.5°F	3	109.0°F	4	289.56BTU	5	0.022 V	6	0 V/
A081:13:40:00 0 67.2°F	1	75.7°F	2	140.3°F	3	109.4°F	4	288.45BTU	5	0.023 V	6	0 V/
A081:13:45:00 0 67.2°F	1	76.4°F	2	140.6°F	3	110.0°F	4	288.10BTU	5	0.023 V	6	0 V/
A081:13:50:00 0 67.3°F	1	77.2°F	2	141.1°F	3	111.0°F	4	287.16BTU	5	0.022 V	6	0 V/
A081:13:55:00 0 68.4°F	1	78.1°F	2	141.5°F	3	111.7°F	4	288.02BTU	5	0.023 V	6	0 V/
A081:14:00:00 0 66.7°F	1	79.1°F	2	141.8°F	3	112.5°F	4	285.01BTU	5	0.023 V	6	0 V/
A081:14:05:00 0 68.2°F	1	80.1°F	2	142.4°F	3	113.3°F	4	285.61BTU	5	0.023 V	6	0 V/
A081:14:10:00 0 68.4°F	1	81.3°F	2	143.0°F	3	114.2°F	4	282.26BTU	5	0.022 V	6	0 V/

A081:14:15:00 0 68.2°F	1 82.1°F	2 143.0°F	3 114.7°F	4 282.43BTU	5 0.023 V	6 0 V/
A081:14:20:00 0 67.7°F	1 83.0°F	2 143.5°F	3 115.7°F	4 281.83BTU	5 0.023 V	6 0 V/
A081:14:25:00 0 68.1°F	1 84.3°F	2 143.8°F	3 116.0°F	4 281.23BTU	5 0.023 V	6 0 V/
A081:14:30:00 0 68.4°F	1 85.2°F	2 144.6°F	3 116.6°F	4 283.04BTU	5 0.024 V	6 0 V/
A081:14:35:00 0 69.7°F	1 86.2°F	2 145.1°F	3 117.3°F	4 278.31BTU	5 0.023 V	6 0 V/
A081:14:40:00 0 67.7°F	1 87.2°F	2 144.9°F	3 118.2°F	4 270.75BTU	5 0.023 V	6 0 V/
A081:14:45:00 0 68.7°F	1 88.1°F	2 145.1°F	3 118.6°F	4 272.13BTU	5 0.023 V	6 0 V/
A081:14:50:00 0 68.2°F	1 89.1°F	2 145.5°F	3 119.4°F	4 266.63BTU	5 0.023 V	6 0 V/
A081:14:55:00 0 68.5°F	1 90.1°F	2 145.4°F	3 119.9°F	4 264.82BTU	5 0.023 V	6 0 V/
A081:15:00:00 0 68.3°F	1 90.9°F	2 145.4°F	3 120.4°F	4 257.61BTU	5 0.023 V	6 11.746 V
081:15:05:00 0 68.6°F	1 92.1°F	2 145.4°F	3 120.9°F	4 255.29BTU	5 0.023 V	6 0 V/
A081:15:10:00 0 67.5°F	1 92.9°F	2 145.3°F	3 121.1°F	4 250.05BTU	5 0.023 V	6 11.600 V
081:15:15:00 0 68.1°F	1 93.9°F	2 145.3°F	3 121.6°F	4 247.64BTU	5 0.023 V	6 0 V/
A081:15:20:00 0 69.4°F	1 94.6°F	2 145.4°F	3 122.1°F	4 243.35BTU	5 0.022 V	6 11.231 V
081:15:25:00 0 69.2°F	1 95.4°F	2 145.4°F	3 122.5°F	4 238.02BTU	5 0.022 V	6 0 V/
A081:15:30:00 0 68.9°F	1 96.4°F	2 145.4°F	3 123.4°F	4 236.56BTU	5 0.022 V	6 11.041 V
081:15:35:00 0 68.0°F	1 97.2°F	2 145.4°F	3 123.2°F	4 232.53BTU	5 0.022 V	6 0 V/
A081:15:40:00 0 69.4°F	1 98.0°F	2 145.6°F	3 123.8°F	4 231.07BTU	5 0.022 V	6 10.775 V
081:15:45:00 0 68.0°F	1 98.9°F	2 145.5°F	3 124.2°F	4 225.74BTU	5 0.022 V	6 0 V/
A081:15:50:00 0 67.8°F	1 99.7°F	2 145.1°F	3 124.3°F	4 221.27BTU	5 0.022 V	6 10.318 V
081:15:55:00 0 68.3°F	1 100.3°F	2 145.3°F	3 124.6°F	4 219.56BTU	5 0.022 V	6 0 V/
A081:16:00:00 0 68.2°F	1 101.2°F	2 145.4°F	3 125.1°F	4 215.09BTU	5 0.022 V	6 0 V/

A081:16:05:00 0 67.8°F	1 101.9°F	2 144.9°F	3 125.3°F	4 207.44BTU	5 0.021 V	6 9.754 V
081:16:10:00 0 68.7°F	1 102.7°F	2 144.5°F	3 125.6°F	4 198.42BTU	5 0.021 V	6 0 V/
A081:16:15:00 0 68.4°F	1 103.1°F	2 143.6°F	3 125.8°F	4 191.47BTU	5 0.022 V	6 0 V/
A081:16:20:00 0 68.0°F	1 103.8°F	2 142.7°F	3 126.1°F	4 179.70BTU	5 0.021 V	6 8.535 V
081:16:25:00 0 67.7°F	1 104.1°F	2 141.3°F	3 126.0°F	4 172.65BTU	5 0.021 V	6 0 V/
A081:16:30:00 0 66.6°F	1 104.9°F	2 140.4°F	3 126.0°F	4 167.59BTU	5 0.021 V	6 0 V/
A081:16:35:00 0 66.9°F	1 105.5°F	2 139.0°F	3 126.0°F	4 161.83BTU	5 0.021 V	6 0 V/
A081:16:40:00 0 66.4°F	1 105.5°F	2 137.7°F	3 126.0°F	4 155.04BTU	5 0.021 V	6 7.217 V
081:16:45:00 0 65.5°F	1 106.1°F	2 136.3°F	3 125.9°F	4 149.80BTU	5 0.021 V	6 0 V/
A081:16:50:00 0 65.6°F	1 105.7°F	2 134.9°F	3 126.0°F	4 145.34BTU	5 0.021 V	6 6.731 V
081:16:55:00 0 64.5°F	1 105.4°F	2 133.2°F	3 125.7°F	4 136.40BTU	5 0.020 V	6 6.271 V
081:17:00:00 0 64.2°F	1 100.1°F	2 126.1°F	3 125.9°F	4 129.45BTU	5 0.020 V	6 5.881 V
081:17:05:00 0 64.5°F	1 95.3°F	2 127.0°F	3 125.8°F	4 121.80BTU	5 0.020 V	6 5.479 V
081:17:10:00 0 63.6°F	1 90.0°F	2 121.3°F	3 125.6°F	4 81.51BTU	5 0.020 V	6 4.984 V
081:17:15:00 0 63.6°F	1 85.6°F	2 95.5°F	3 125.5°F	4 12.111BTU	5 3.121 V	6 4.362 V
081:17:20:00 0 63.3°F	1 81.5°F	2 88.1°F	3 125.5°F	4 11.596BTU	5 3.121 V	6 3.926 V
081:17:25:00 0 53.7°F	1 78.2°F	2 83.0°F	3 125.3°F	4 11.081BTU	5 3.121 V	6 0.833 V
081:17:30:00 0 53.7°F	1 75.5°F	2 79.4°F	3 125.3°F	4 9.706BTU	5 3.121 V	6 0.715 V
081:17:35:00 0 53.0°F	1 73.4°F	2 77.0°F	3 125.0°F	4 8.074BTU	5 3.122 V	6 0.603 V
081:17:40:00 0 53.7°F	1 71.0°F	2 74.7°F	3 124.9°F	4 6.957BTU	5 3.122 V	6 0.544 V
081:17:45:00 0 54.3°F	1 69.4°F	2 73.1°F	3 125.0°F	4 6.442BTU	5 3.121 V	6 0.488 V
081:17:50:00 0 54.1°F	1 67.7°F	2 71.4°F	3 124.9°F	4 5.497BTU	5 3.122 V	6 0.429 V

081:17:55:00 0 54.4°F	1	66.7°F	2	69.9°F	3	125.6°F	4	4.7248BTU	5	3.121 V	6	0.371 V
081:18:00:00 0 54.5°F	1	65.6°F	2	68.6°F	3	124.6°F	4	3.6078BTU	5	3.121 V	6	0.312 V
081:18:05:00 0 54.7°F	1	64.8°F	2	67.4°F	3	124.7°F	4	2.7468BTU	5	3.122 V	6	0.257 V
081:18:10:00 0 54.4°F	1	63.9°F	2	66.2°F	3	124.5°F	4	1.8039BTU	5	3.121 V	6	0.200 V
081:18:15:00 0 54.6°F	1	63.1°F	2	65.0°F	3	124.5°F	4	1.2026BTU	5	3.122 V	6	0.147 V
081:18:20:00 0 55.0°F	1	62.3°F	2	63.9°F	3	124.4°F	4	0.0000BTU	5	3.121 V	6	0.097 V
081:18:25:00 0 55.7°F	1	61.8°F	2	62.8°F	3	124.4°F	4	-0.0859BTU	5	3.122 V	6	0.058 V
081:18:30:00 0 55.3°F	1	61.1°F	2	61.8°F	3	124.2°F	4	-0.6013BTU	5	3.121 V	6	0.033 V
081:18:35:00 0 55.3°F	1	60.6°F	2	60.9°F	3	124.2°F	4	-0.8590BTU	5	3.121 V	6	0.020 V
081:18:40:00 0 55.1°F	1	60.1°F	2	59.9°F	3	124.0°F	4	-0.9449BTU	5	3.121 V	6	0.014 V
081:18:45:00 0 55.0°F	1	59.6°F	2	59.3°F	3	123.9°F	4	-0.9449BTU	5	3.121 V	6	0.013 V
081:18:50:00 0 54.5°F	1	59.0°F	2	58.5°F	3	123.8°F	4	-0.7731BTU	5	3.122 V	6	0.013 V
081:18:55:00 0 54.7°F	1	58.7°F	2	58.0°F	3	123.8°F	4	-0.9449BTU	5	3.121 V	6	0.012 V
081:19:00:00 0 54.8°F	1	58.3°F	2	57.4°F	3	123.7°F	4	-0.6872BTU	5	3.122 V	6	0.012 V
081:19:05:00 0 54.3°F	1	57.9°F	2	56.7°F	3	123.6°F	4	-0.3436BTU	5	3.121 V	6	0.012 V
081:19:10:00 0 54.0°F	1	57.6°F	2	56.3°F	3	111.5°F	4	-0.7731BTU	5	3.122 V	6	0.013 V
081:19:15:00 0 54.4°F	1	57.4°F	2	55.9°F	3	95.1°F	4	-0.6013BTU	5	3.121 V	6	0.012 V
081:19:20:00 0 53.7°F	1	57.1°F	2	55.6°F	3	90.4°F	4	-0.6872BTU	5	3.121 V	6	0.013 V
081:19:25:00 0 53.7°F	1	56.6°F	2	54.9°F	3	90.4°F	4	-0.5154BTU	5	3.122 V	6	0.012 V
081:19:30:00 0 53.2°F	1	56.3°F	2	54.5°F	3	89.6°F	4	-0.6872BTU	5	3.121 V	6	0.013 V
081:19:35:00 0 53.2°F	1	55.9°F	2	54.0°F	3	89.5°F	4	-0.5154BTU	5	3.121 V	6	0.012 V
081:19:40:00 0 53.1°F	1	55.8°F	2	53.8°F	3	89.6°F	4	-0.8590BTU	5	3.121 V	6	0.012 V

081:19:45:00 0 53.1°F	1	55.4°F	2	53.5°F	3	89.3°F	4-0.2577RTU	5	3.121 V	6	0.012 V
081:19:50:00 0 53.2°F	1	55.3°F	2	53.3°F	3	89.2°F	4-0.5154RTU	5	3.121 V	6	0.012 V
081:19:55:00 0 53.0°F	1	55.2°F	2	53.0°F	3	89.1°F	4-0.1718RTU	5	3.121 V	6	0.012 V
081:20:00:00 0 53.6°F	1	55.1°F	2	52.9°F	3	89.1°F	4 0.0000RTU	5	3.122 V	6	0.013 V
081:20:05:00 0 52.9°F	1	55.0°F	2	52.5°F	3	88.8°F	4-0.6872RTU	5	3.121 V	6	0.013 V
081:20:10:00 0 52.7°F	1	54.7°F	2	52.3°F	3	88.7°F	4-0.6872RTU	5	3.121 V	6	0.012 V
081:20:15:00 0 52.7°F	1	54.5°F	2	52.1°F	3	88.6°F	4-0.7731RTU	5	3.121 V	6	0.012 V
081:20:20:00 0 52.4°F	1	54.1°F	2	51.7°F	3	88.1°F	4-0.8590RTU	5	3.121 V	6	0.013 V
081:20:25:00 0 52.1°F	1	53.7°F	2	51.4°F	3	87.7°F	4-0.8590RTU	5	3.122 V	6	0.013 V
081:20:30:00 0 52.3°F	1	53.7°F	2	51.3°F	3	87.5°F	4-0.5154RTU	5	3.122 V	6	0.012 V
081:20:35:00 0 52.4°F	1	53.4°F	2	51.1°F	3	87.0°F	4-0.4295RTU	5	3.122 V	6	0.012 V
081:20:40:00 0 52.5°F	1	53.2°F	2	50.8°F	3	86.7°F	4-0.2577RTU	5	3.121 V	6	0.012 V
081:20:45:00 0 52.2°F	1	52.9°F	2	50.4°F	3	85.9°F	4 0.0000RTU	5	3.121 V	6	0.012 V
081:20:50:00 0 52.0°F	1	52.7°F	2	50.1°F	3	85.3°F	4 0.0000RTU	5	3.122 V	6	0.013 V
081:20:55:00 0 52.1°F	1	52.8°F	2	50.1°F	3	84.8°F	4 0.0000RTU	5	3.122 V	6	0.013 V
081:21:00:00 0 52.2°F	1	52.6°F	2	50.0°F	3	84.4°F	4-0.5154RTU	5	3.121 V	6	0.013 V
081:21:05:00 0 52.3°F	1	52.4°F	2	49.7°F	3	83.7°F	4-0.0859RTU	5	3.121 V	6	0.012 V
081:21:10:00 0 51.8°F	1	52.0°F	2	49.5°F	3	83.1°F	4 0.0000RTU	5	3.122 V	6	0.013 V
081:21:15:00 0 51.5°F	1	51.8°F	2	49.3°F	3	82.5°F	4 0.0000RTU	5	3.121 V	6	0.012 V
081:21:20:00 0 51.4°F	1	51.6°F	2	49.3°F	3	82.0°F	4 0.0000RTU	5	3.122 V	6	0.013 V
081:21:25:00 0 51.3°F	1	51.5°F	2	49.1°F	3	81.4°F	4-0.4295RTU	5	3.121 V	6	0.012 V
081:21:30:00 0 51.0°F	1	51.0°F	2	48.7°F	3	80.6°F	4-0.4295RTU	5	3.121 V	6	0.012 V

081:21:35:00 0 51.0°F	1	50.8°F	2	48.6°F	3	80.2°F	4-0.3436BTU	5	3.122 V	6	0.013 V
081:21:40:00 0 51.3°F	1	50.7°F	2	48.3°F	3	79.7°F	4-0.3436BTU	5	3.122 V	6	0.013 V
081:21:45:00 0 50.4°F	1	50.5°F	2	48.3°F	3	79.0°F	4 0.0859BTU	5	3.122 V	6	0.013 V
081:21:50:00 0 51.1°F	1	50.3°F	2	48.1°F	3	78.5°F	4 0.0000BTU	5	3.121 V	6	0.013 V
081:21:55:00 0 51.1°F	1	50.2°F	2	48.1°F	3	77.9°F	4 0.0000BTU	5	3.121 V	6	0.012 V
081:22:00:00 0 51.3°F	1	50.2°F	2	48.2°F	3	77.4°F	4 0.2577BTU	5	3.122 V	6	0.013 V
081:22:05:00 0 51.1°F	1	50.3°F	2	48.1°F	3	76.9°F	4 0.0000BTU	5	3.121 V	6	0.012 V
081:22:10:00 0 50.8°F	1	50.2°F	2	47.9°F	3	76.1°F	4 0.0000BTU	5	3.121 V	6	0.012 V
081:22:15:00 0 50.8°F	1	50.1°F	2	47.9°F	3	75.7°F	4 0.0000BTU	5	3.121 V	6	0.012 V
081:22:20:00 0 50.5°F	1	50.1°F	2	47.9°F	3	75.1°F	4-0.6872BTU	5	3.122 V	6	0.012 V
081:22:25:00 0 50.5°F	1	49.9°F	2	47.7°F	3	74.7°F	4-0.2577BTU	5	3.122 V	6	0.013 V
081:22:30:00 0 50.4°F	1	49.9°F	2	47.6°F	3	74.2°F	4-0.2577BTU	5	3.122 V	6	0.013 V
081:22:35:00 0 50.1°F	1	49.8°F	2	47.5°F	3	73.7°F	4-0.6872BTU	5	3.121 V	6	0.013 V
081:22:40:00 0 50.4°F	1	49.7°F	2	47.4°F	3	73.5°F	4 0.0000BTU	5	3.121 V	6	0.012 V
081:22:45:00 0 50.1°F	1	49.6°F	2	47.4°F	3	72.8°F	4-0.2577BTU	5	3.121 V	6	0.012 V
081:22:50:00 0 50.5°F	1	49.6°F	2	47.4°F	3	72.5°F	4 0.0000BTU	5	3.121 V	6	0.013 V
081:22:55:00 0 50.4°F	1	49.5°F	2	47.4°F	3	71.9°F	4 0.0000BTU	5	3.121 V	6	0.012 V
081:23:00:00 0 50.6°F	1	49.5°F	2	47.5°F	3	71.5°F	4 0.0000BTU	5	3.121 V	6	0.013 V
081:23:05:00 0 50.1°F	1	49.5°F	2	47.3°F	3	71.1°F	4-0.6013BTU	5	3.121 V	6	0.013 V
081:23:10:00 0 49.7°F	1	49.3°F	2	47.1°F	3	70.7°F	4-0.4295BTU	5	3.121 V	6	0.012 V
081:23:15:00 0 49.4°F	1	49.3°F	2	46.9°F	3	70.3°F	4 0.0000BTU	5	3.121 V	6	0.012 V
081:23:20:00 0 49.6°F	1	49.1°F	2	46.6°F	3	69.9°F	4-0.3436BTU	5	3.121 V	6	0.013 V